

# Brief communication: Tritium concentration and age of firn accumulation in an ice cave of Mt. Olympus (Greece) – Response to the referees

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## Response to referee #1

### General comments

15 This paper presents a new series of tritium measurements from firn sampled in an underground ice deposit of Mount Olympus. The lack of the so-called 'Tritium bomb peak' in the series (all current values are under 10 TU) is interpreted as evidence for a maximum age of ~50 years for the ice deposit of Christaki cave. I recommend this communication for publication, provided some significant changes are made to the manuscript.

20 From the cave survey and the geometry of the ice body however, I believe there are limitations on the conclusions about the age of the ice deposit in this cave. It appears that there are indeed, according to the survey some deep ice layers that you could not access for sampling, which may have yielded the tritium peak. In this case, the maximum age of the ice could be older still. I stress that since the ~2 m sampled section was deposited in at most 50 years, the minimum rate of ice accumulation interpreted by the authors remains valid. I would encourage the authors to discuss the possibility of older ice being present, but inaccessible in the discussion, rather than the final line of the conclusion.

25 I feel this short communication is a relevant contribution as it provides evidence for a minimum mean annual mass balance in high elevation ice caves, which are still under researched objects of the cryosphere.

In general, the quality of the English could be significantly improved. A mix of British and American English was noted in the text (e.g., analysed in the Abstract, meters in the main body of text). Please see the technical comments for suggestions.

### 30 Specific comments

- I think the title should contain ice cave in the singular, because although there is a mention of neighbouring cave on mount Olympus, the age determination is only carried out at one of these sites. I say this because the geometry constraints of each cave may permit the accumulation of firn bodies with varying thicknesses and age within a very small karst area.

35 ***We changed the title according to the reviewer's suggestion.***

- From figure S3, it looks like there are organic debris falling into the entrance shaft of the Christaki pothole. I think a way to continue/ corroborate this report would be radiocarbon dating any organic inclusions found in the ice. One would expect idea a fraction modern F14C > 1 from one such sample, given the hypothesis of 'young' firn in the caves of these areas.

40 ***We thank the reviewer for this suggestion. It is among our future goals to use radiocarbon dating to access the age of ice accumulation in the caves of Mt. Olympus.***

- In several places, an 'ice column' is mentioned, which I assume is the section of ice that was sampled for tritium measurements. I would suggest changing this to 'ice section', because it might otherwise be confused with a pillar shaped congelation ice speleothem.

45 ***We changed the word “column” to “section”.***

- At the end of the introduction, I would also introduce previous ice cave studies which dealt with ice dating using the tritium peak, either present (1) or absent (2).

***The phrase “Previous studies have date ice deposits by using the tritium peak, which was either present (Kern et al., 2009) or absent (Kern et al., 2011).” is added at the end of the introduction.***

50 • At line 45, high average snow fall is mentioned - this could do with a citation and quantitative estimate of e.g., mean snow depth.

***By this sentence we wanted to emphasize on the high snowfall. Its depth can reach 3m in the area of the cave and the Christaki refuge. However, a reference is missing. So, we changed this phrase in order to use published information and provide some impression of the snowfalls in Mt. Olympus. “The amount of precipitation in combination with the high altitude, leads to snowfalls even during summer season (Sahsamanoglou, 1989).”***

55 • Lines 60-66 - I find the line of reasoning hard to follow. You observe that every sample contains soil debris and dust, a material which was deposited onto the ice deposit during the summer period. You argue that ablation and overburden by new snow the following winter result in the dissemination of the material within the existing firn, thus obscuring the layers, making them indistinguishable. You then infer that the maximum single annual layer thickness could not exceed that of the current ice deposit? If so, I do not see how it helps the following reasoning.

60 ***We realized that this part of the text was hard to follow, and we agree with the reviewer. We deleted the sentence 64-66 that was not adding to the reasoning about the age of the ice body and we did some improvements to the lines 60-64.***

65 • I think sentence 64-66 could be deleted or made clearer in the text why it adds to the reasoning about the maximum age of the ice body.

***We agree with the reviewer and thus we deleted the phrase.***

70 • Lines 66-71 - this section of the text contains the main line of argument - i.e., corrected for decay, one would expect a > 130 TU tritium peak in an ice deposit whose age exceeds 50 years, provided there are no hiatuses and provided the ice in the cave is not relict ice, currently melting. I think you have observations that show the snow surface is not ancient, but melts from the bottom. I have added some technical comments to have this section read better.

***We followed all the related technical comments suggested by the reviewer below.***

75 • Figure 1 - I think that this figure would benefit from a simplified overview map of the central Mediterranean region (currently Figure S1), showing where exactly the site is in relation to the coastlines and maybe other known/published ice bearing sites from the Greek ice cave cadastre (this would serve to highlight and support the statement about how widespread ice caves are in Greece). I propose this because there is left-over width in the figure, so adding another small panel could help. Is the scale on Panel B the same as that of Panel A?

80 *Figure 1 is changed according to the reviewer's suggestion.*

Technical corrections

- 112: 'sharp raise of tritium' should read 'sharp rise of tritium' or 'sharp tritium peak'
- 114: It should probably be reworded to make clear here that the absence of the tritium peak provides an upper age limit for the deepest layer of the ice deposit.
- 85 • 118-19: 'and distribution': I am not sure what is meant here. The sentence could be reworded to make it clear that the classification scheme proposed by Luetscher and Jeannin (2004) helps differentiate ice caves based on their morphology (hence ventilation pattern) and the type of ice they contain (primarily firn, or congelation ice).
- 122: 'have been exploited for years...' should read 'has been exploited for years between the end of the 19th Century and the 1950s'
- 90 • 123: 'to villages and and town at the foothills' should read 'to villages and towns in the foothills'
- 125 'were applied at' should read 'were carried out at'
- 126-28: this pair of sentences would benefit from citations, eg: (3) (4)
- 130 'resulting to a sharp peak' should read 'resulting in a sharp peak', also could use citation (5)
- 95 • 131-32: could be better formulated such as: 'up to 6,000 TU in Canada and Austria, reached in 1953 and 1961, respectively (Cauquoin et al., 2016).'
- 133-34: could be reformulated: 'The tritium peaks in precipitation of the early 1960s ...'
- 135: 'on the NW slope of the mountain' could read 'on the NW slope of mount Olympos'
- 136: 'the list of ice caves in Greece' could be reformulated as 'the Greek ice cave cadaster'
- 100 • 137: replace 'first descent' with 'entrance pit'
- 140: 'progressively goes thicker to the west, reaching about 4.5 m of thickness' could read 'progressively thickening westwards, reaching a maximal thickness of 4.5 m'
- 140-41: again maybe reformulate to: 'The ice plug prevents any access to the westward continuation of the cave'.
- 105 • 142: 'is consisted of' should either read 'is composed of' OR 'consists of'
- 143 'gradually reduce their composition to dolomite' should read 'gradually transition to dolomite'
- 143-45: reformulating the sentence so it could read 'The western slopes of Mount Olympos act as a barrier to the hot and humid westerly air masses and thus experience enhanced orographic precipitation'.
- 152 'from a section of 2 m high' should read 'from a 2 m high section (Figure 1A)'

- 110
- 153: 'in 5cm intervals' should read 'at 5 cm intervals'
  - 154: 'chosen to be measured for tritium' could read 'selected for tritium content determination'
  - 155: could reformulate to have no number at the start of the sentence? e.g., 'For each sample, 8 mL of melted ice were ...'
- 115
- 160: I think this sentence could be reformulated to highlight the fact the lack of layers precluded the estimate of the age of the ice deposit by layer counting.
  - 164: I don't think incineration is the correct word: 'dissemination' perhaps?
  - 166-67 I would reformulate the sentence to 'Since the cave firn deposit was thought to have accumulated for many decades, it was hypothesised that the above-mentioned atmospheric tritium peak would be found in the melted ice samples'.
- 120
- 170: 'could be resulted from' should read 'could result from'
  - 171: 'annual mean tritium' should read 'mean annual tritium'
  - 177: The sentence could be reformulated thus: 'Considering this upper limit of 50 years for the base of ice deposit, the corresponding mean winter snow layer thickness is at least 4 cm y<sup>-1</sup>'.
  - 181: capitalise 'Croatian ice cave'.
- 125
- 183: Sentence could be reformulated thus: 'However, these estimates do not date the onset of cave glaciation, nor times at which the cave may have been completely ice free'.

*All the above technical corrections have been followed (lines 83-126).*

- 184: could you provide a reference for this statement?

130 *Actually, this was an indirect assumption that is provided to support the possibility of ice melting when it comes in contact with the bedrock. We changed the phrase, and we added two references that support this statement.*

Suggested References:

- (1) Kern et al, 2009 High-resolution, well-preserved tritium record in the ice of Bortig Ice Cave, Bihor Mountains, Romania
  - (2) Kern et al, 2011, Isotope hydrological studies of the perennial ice deposit of Saarlhalle, Mammuthöhle, Dachstein Mts, Austria
  - (3) L.L. Lucas, M.P. Unterweger Comprehensive review and critical evaluation of the half-life of tritium J. Res. Natl. Inst. Stand. Technol., 105 (4) (2000), pp. 541-549
  - (4) D.H. Ehhalt, F. Rohrer, S. Schauffler, W. Pollock Tritiated water vapor in the stratosphere: vertical profiles and residence time J. Geophys. Res., 107 (D24) (2002), p. 4757, 10.1029/2001JD001343
  - (5) E.A. Martell On the inventory of artificial tritium and its occurrence in atmospheric methane J. Geophys. Res., 68 (1963), pp. 3759-3769
- 140

*All the above references were very useful and were added to the manuscript.*

**Response to referee #2**

- 145 1. As a basic requirement site photos and/or sketched stratigraphic profile should be mandatory to understand the sampling strategy and see the visual occurrence of the deposit and the sampling spots. In lack of such evidence a statement like "indistinguishable ice layers and thus it was impossible to make a direct estimation of the age of the ice in the column." " is unsubstantiated.

150 *Due to the ablation of the firn (late September sampling period) there was no clear evidence of the stratigraphy as can be derived from the provided photo. So, the sampling strategy was to take samples in a subsequent way, also as seen in the provided photo, although not clearly.*

2. Methodological description needs some more details. E.g., Did you apply electrolytic enrichment? If yes please give some details, if no please mention that. What was the critical limit and/or detection limit?

155 *We did not perform electrolytic enrichment because the Laboratory does not have well established curves of tritium enrichment efficiencies (line 68). The detection limit is added in the text (Detection Limit =  $3\sqrt{B}/(T \text{ eff } V a)$  where  $B$ =background counts,  $T$ = measurement time (min),  $\text{eff}$ =efficiency of the detector for Tritium=0.25,  $V$ =8mL,  $a$ =0.11919 Bq/L/TU)  $DL=1.2$  TU. All mentioned in lines 71-75 in revised manuscript.*

- 160 3. The caption of Fig 2 says that the annual mean tritium values of various Greek stations are used as reference. It is not a bad approach however I think it would be necessary to show the location of the considered stations in a map. (By the way, Fig 1 should be completed with an additional panel showing the location of the cave, so the nearest GNIP stations can be marked in this map.)

*Table with the stations GNIP in Greece. Short introduction is added in the caption of Fig. 2 and this table in the supplement.*

<i>Site</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Altitude</i>
<i>Alexadroupolis</i>	<i>40.849998</i>	<i>25.879999</i>	<i>6</i>
<i>Athens</i>	<i>37.900002</i>	<i>23.73</i>	<i>27</i>
<i>Heraklion</i>	<i>35.330002</i>	<i>25.18</i>	<i>47</i>
<i>Methoni</i>	<i>36.830002</i>	<i>21.719999</i>	<i>33</i>
<i>Patras</i>	<i>38.279999</i>	<i>21.790001</i>	<i>100</i>
<i>Rhodes</i>	<i>36.380001</i>	<i>28.1</i>	<i>42</i>
<i>Thessaloniki</i>	<i>40.669998</i>	<i>22.959999</i>	<i>32</i>
<i>Ioannina (non GNIP)</i>	<i>39.663611</i>	<i>20.852222</i>	<i>480</i>
<i>Christaki pothole</i>	<i>40.068954</i>	<i>22.313373</i>	<i>2290</i>

- 165 4. However, I suggest considering the prediction from the recently released study (Terzer-Wassmuth et al., 2022) as a reference or as a continuous interpolated product covering the 1950 to 2010 period (Jasechko&Taylor 2015) could be used.
- 170 a. Terzer-Wassmuth, S., Araguás-Araguás, L.J., Copia, L. et al. High spatial resolution prediction of tritium (3H) in contemporary global precipitation. Sci Rep 12, 10271 (2022). <https://doi.org/10.1038/s41598-022-14227-5>
- b. Jasechko, S., & Taylor, R. G. (2015). Intensive rainfall recharges tropical groundwaters. Environmental Research Letters, 10(12), 124015

175 *Studying the Terzer-Wassmuth et al. (2022) paper we tried to predict tritium values in the investigation area using the models provided but the calculated values were obviously very high maybe due to the misunderstanding of the parameters and their values that must be used for the site. In any case the map provided for the area of Greece give values of tritium concentrations in the range we measured in our Laboratory.*

- 180 5. The authors explain why the studied ice samples could not represent accumulation from the so-called bomb-peak period. However, I think, it should be also explained in a sentence or in a brief section how they can exclude pre-1950 origin.

185 *The samples were collected from the top of the firn to a depth of 2 meters in a back-to-back way. Thus, the samples from the top are from the previous years. If there were ice residues from years before 50s then we should measure at some samples high tritium concentrations from the 60s as mentioned in detail into the manuscript. Short discussion is added into the manuscript (lines 98-99).*

#### Technical revisions

line 13: I think “indicating” would be a more suitable word here instead of “because”. In addition, the range of the measured 3H activities could be mentioned in the abstract.

*Followed in lines 13-14*

190 line 18: I suggest citing the chapter (Pennos et al., 2018) of the Ice Cave Book here. *Pennos, C., Styllas, M., Sotiriadis, Y., and Vaxevanopoulos, M.: Ice caves in Greece, in: Ice caves, edited by: Persoiu, A. and Lauritzen, S. E., Elsevier, Amsterdam, the Netherlands, 385-397, <https://doi.org/10.1016/B978-0-12-811739-2.00018-8> 2018.*

195 *The research that we mention (Lazaridis et al., 2018) contains data from 76 caves, the one that is suggested here contains only three of the already included in the mentioned research caves. We thank the referee for the comment, but we don't find useful and necessary the suggested citation.*

line23: I think a supporting reference for this statement is needed.

200 *Unfortunately, there is not a reference for this statement. The information comes from interviews with local people. However, we find it very interesting and useful to publish.*

line26: I think Lucas&Unterweger 2000 should be cited after the half-life of tritium. *Lucas, L.L. and Unterweger, M.P. 2000: Comprehensive review and critical evaluation of the halflife of tritium. Journal of Research of the National Institute of Standards, Technology 105, 541–49.*

205 *The suggested reference was added and the Ehhalt et al. 2002 as well.*

lines31-32: I think the end of this sentence seems to be a fragment which can be deleted.

*The sentence has already been modified due to a comment from the first referee.*

210

line42-43: Why these info (e.g., total thickness of limestone sequence, dolomitic composition) is useful for this study?

*We believe that is very useful to describe the setting of the cave and the geology of the area and we consider it as necessary information.*

215

line 44: I suspect you should replace “gas” with “air”.

*The sentence has already been modified due to a comment form the first referee.*

line46: Please give numerical expression for “high average snowfall”.

220

*The sentence has already been modified due to a comment form the first referee.*

lines6 60-61: Unclear sentence. Did you mean that ice layers (or any stratigraphic units) were indistinguishable in the sampled ice column?

*The sentence has already been modified due to a comment form the first referee.*

225

line 68: I suggest replacing “0.9-11” with “0.9 to 11”.

*The suggestion was followed.*

line81: I think 210Pb should be written instead of “radon”. In addition, please, capitalize Croatia in the same line.

230

*Replaced and correctly spelled line 105*

Finally, I think a recent TC paper (<https://doi.org/10.5194/tc-15-2383-2021>) should be considered in an extended discussion since similar deposits were considered also in that study.

235

*We followed the suggestion, we consulted the paper and added to the references.*

In an ultimate comment I’d like to refer to the other review. I completely agree with the comments and suggestions of Dr Tanguy Racine. A related suggestion is that beside 2011 paper about Mammuthöhle ice cave I suggest that a more recent one (DOI:10.1017/RDC.2018.96) could be a more useful reference for the revision.

*The suggestion was followed as we find the research relevant and necessary to refer to.*